

# Oscilloscope Basics

## Primer

### Abstract:

The oscilloscope is arguably one of the most useful general purpose tools ever created for use by electronic engineers. Since its invention more than 100 years ago, new types, features and functionalities have been introduced.

As automated measurements become ever more complex, many of the key considerations, such as probing, sampling, vertical and horizontal system, and trigger stability remain the same. It's therefore important for the user to understand the underlying technology to get the most benefit out of his or her oscilloscope.

This primer provides an overview of the basic, but most important building blocks of an oscilloscope as it relates to specifications, limitations and impact on measurement accuracy.

### Note:

Please find more educational resources on oscilloscopes by visiting

<http://www.rohde-schwarz-usa.com/Scope-Resources.html>

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# 1 Introduction

This white paper provides a review of oscilloscope fundamentals. The probing basics covers both passive and active probing, including the effects of probe compensation and using different ground leads. This is followed by an overview on the vertical system. We'll discuss input coupling, how to effectively use the vertical scale and ways to get additional oscilloscope resolution.

We'll then look at sampling methods and acquisition rates covering horizontal systems, along with the relationship of oscilloscope memory depth and the sample rate. Finally we'll discuss the trigger system. Trigger specifications to pay attention to as well as the different advanced triggers that are available in most modern oscilloscopes.

Throughout this white paper the [R&S@RTE series oscilloscope](#) is used as an example, but the majority of the material is oscilloscope agnostic so it could be any other oscilloscope.

## 2 Oscilloscope Basics

Oscilloscopes have been around for a very long time, since they were first invented in the 1930s. In the beginning all oscilloscopes were analog. As digital technologies advanced oscilloscopes have since moved from being analog to digital, and more features and measurement functionalities have been added, but some of the key basic considerations still remain the same.

### 2.1 The Importance of Bandwidth

Oscilloscope bandwidth is typically the number one specification that somebody looks at when determining what oscilloscope to buy. Fig. 2-1 shows the typical frequency response of an oscilloscope, which is basically often a Gaussian curve. As the frequency increases the signal eventually starts to die off. Oscilloscope bandwidth is specified at the -3 dB or a 3 dB down point. Therefore the maximum bandwidth of an oscilloscope is defined as the frequency at which a sinusoidal input signal amplitude is attenuated by -3dB.

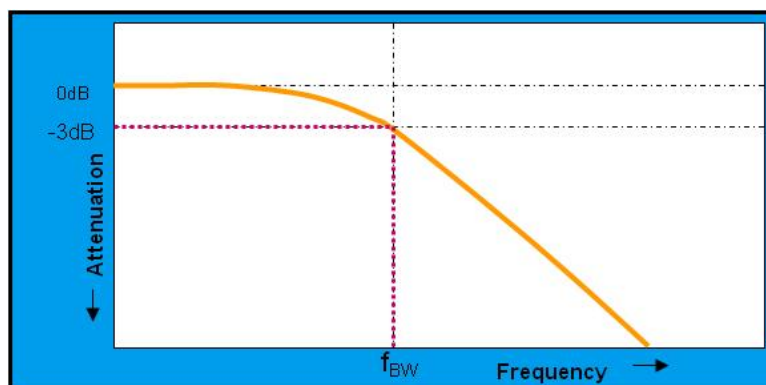


Fig. 2-1: Maximum bandwidth of an oscilloscope is defined as the frequency at which a sinusoidal input signal amplitude is attenuated by -3dB

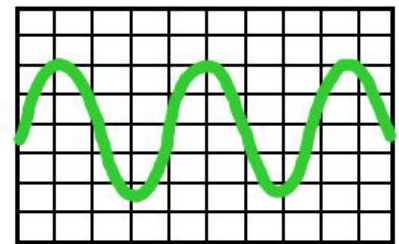
So what does this mean? Let's take an example 50 kHz sine wave signal. In this example it would be 6 divisions with zero attenuation (Fig. 2-2a). As you get near the end of where the oscilloscope is specified and you get to that -3 dB down point, you'll see that this signal is now 4.2 divisions (Fig. 2-2b). This means that about 30 percent of the actual signal amplitude has been lost.

So will you be able to capture additional frequencies beyond the bandwidth of the oscilloscope? More than likely, but keep in mind that those will continue to be attenuated as you go beyond the maximum bandwidth or the maximum specified bandwidth of the oscilloscope itself.



**0 dB**  
**6 div at 50 kHz**

(2-2a) Within the specified bandwidth



**- 3 dB**  
**4.2 div at bandwidth**

(2-2b) At the 3 dB point

Fig. 2-2: Measuring signals beyond the bandwidth of the oscilloscope will result in attenuation of the signal

## 2.2 Choosing the Right Bandwidth

To determine the required oscilloscope bandwidth we need to consider the requirements for the signal under test. In the previous section we said that the bandwidth of the oscilloscope should not exceed the maximum frequency of the test signal, but most signals are much more complex than a simple sine wave. This means that the test signal harmonics should fall within the bandwidth as well.

A typical rule of thumb is that the bandwidth of the oscilloscope should be somewhere between 3x to 5x the clock frequency of the test signal. For a digital signal you typically want to see the fifth harmonic. For example, let's take a 200 MHz signal with a 200 MHz clock rate. In order to properly measure out to the 5th harmonic, an oscilloscope with 1 GHz of bandwidth should be used.

For an analog signal you don't necessarily need to see the fifth harmonic. Sometimes just seeing the third harmonic is acceptable. In this case getting an oscilloscope with enough bandwidth to cover three times the clock frequency is recommended.

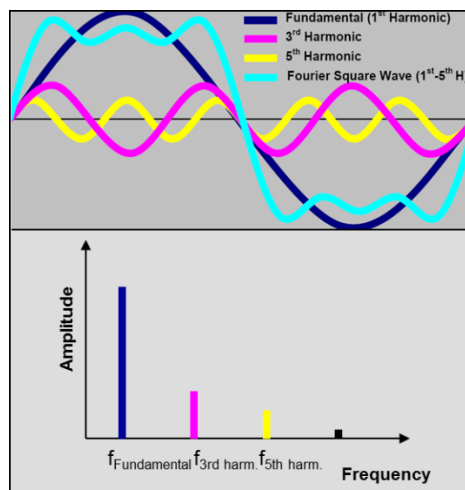


Fig. 2-3: Determining your oscilloscope bandwidth needs

## 2.3 Bandwidth Required for Specific Applications

Table 2-1 shows some different applications to put this in perspective. For each of the different interfaces the table highlights the data rate, clock frequency, the oscilloscope bandwidth required to see both the third and the fifth harmonic, and the class of oscilloscope required.

Let's use I2C as an example. I2C is a very common interface with a relatively low speed. It runs at 3.4 Mbps, which has a clock frequency of around 1.7 MHz. In order to measure the fifth harmonic, the oscilloscope would need a bandwidth of 8.5 MHz. Today most oscilloscopes have significantly more bandwidth than that, so this application typically falls into the value range of oscilloscopes.

Let's consider the USB 2.0 interface that is very common but runs at a higher speed at 480 Mbps. That means the clock frequency is running at 240 MHz. In order to see the fifth harmonic on USB 2.0 you'll need a scope with 1.2 GHz of bandwidth. That's starting to move into more of a midrange oscilloscope.

Finally, let's consider a much higher speed bus, something like PCI Express 2.0 which runs at 5.0 Gbps with a clock frequency running at 2.5 GHz. In order to see the fifth harmonic of that signal requires an oscilloscope with 12.5 GHz of bandwidth. This application would require a higher end oscilloscope to achieve that high of a frequency.

Table 2-1: Required Application Bandwidths

Interface	Data Rate	Clock Frequency	Oscilloscope Bandwidth Requirement		Oscilloscope Classes
			3rd harmonic	5th harmonic	
I2C	3.4 Mbps	1.7 MHz	5.1 MHz	8.5 MHz	Value
LAN 1G	125 Mbps	62.5 MHz	187.5 MHz	312.5 MHz	Lower mid-range
USB 2.0	480 Mbps	240 MHz	720 MHz	1200 MHz	Mid-range
DDR II	800 Mbps	400 MHz	1.2 GHz	2.0 GHz	
SATA I	1.5 Gbps	750 MHz	2.25 GHz	3.75 GHz	Upper Mid-range
PCIe 1.0	2.5 Gbps	1.25 GHz	3.75 GHz	6.25 GHz	High-end entry
PCIe 2.0	5.0 Gbps	2.5 GHz	7.5 GHz	12.5 GHz	High-end



## 3 Probing Basics

Probing is one of the more overlooked areas but is equally as important as the bandwidth of the oscilloscope. If the signal going into the oscilloscope is being distorted by the probe, then it doesn't matter how much bandwidth the oscilloscope has or how good of an oscilloscope it is - you're going to end up with incorrect measurements.

From a basic probe standpoint there are three factors to pay attention to. First is the physical attachment of the probe to the device under test. Second is to minimize the impact on the device under test. Third is to ensure adequate signal fidelity, making sure that what is seen on the oscilloscope is the most accurate representation of what's actually happening on the device under test.

### 3.1 An Ideal Probe

First let's consider an ideal probe. The ideal probe does not influence your device under test and would display the original signal on the oscilloscope without any distortion. For example, consider the setup in [Fig. 3-1](#). There are two chips and the measurement is probing the bus in between them. The original signal is shown on the left. After attaching the ideal probe, what that receiver would see is exactly the original signal that was measured before the the probe was attached. At the oscilloscope, ideally what is shown is exactly what is happening on the bus.

Unfortunately an ideal probe doesn't really exist and so in reality there will be some type of impact from the probe on the measurement. The goal is to minimize that impact.

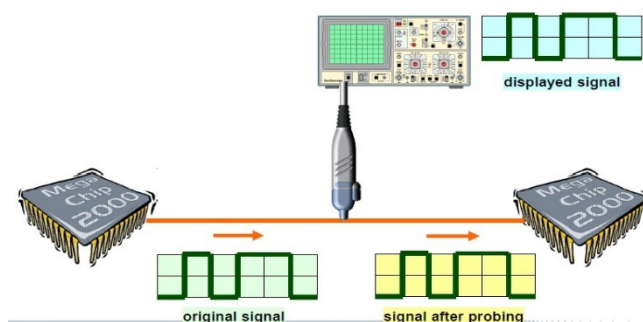


Fig. 3-1: An ideal probe would have no impact on the measured signal.

Now with the exact same setup again, let's consider a real probe. The original signal is still the same, but after the probe is attached it is most likely going to have some impact on that signal. This in turn is going to affect what the receiver and the chip down the line sees. Fig. 3-2 shows the modified signal here in the red. At the oscilloscope, the probe is most likely also going to have some sort of impact. The main goal when selecting a probe is to try to minimize this impact as much as possible.

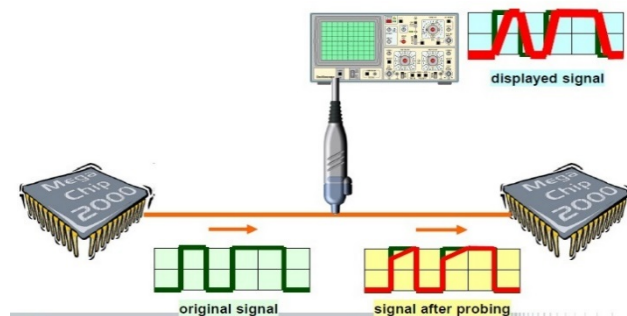


Fig. 3-2: All probes will have an impact on the measured signal. The goal is to select a probe that will minimize the effect.

## 3.2 Passive Probes

The most common and least expensive type of probe is a passive probe. It is what traditionally delivered with the oscilloscope, usually one per channel. Passive probes are also the most robust. They typically have no active components and are essentially a wire with an RC network. Generally when ordering a 500 MHz oscilloscope it will come with passive probes that also have 500 MHz of bandwidth.

One thing to keep in mind about passive probes is that while they may be specified at a certain bandwidth, there is a potential that the input impedance of the probe itself is going to decrease as you go up in frequency. Fig. 3-3 shows a typical example of the performance of the passive probe. As the probe is used at higher frequency signals, the input impedance of the probe is going to decrease and that will end up having a more significant impact on the device under test.

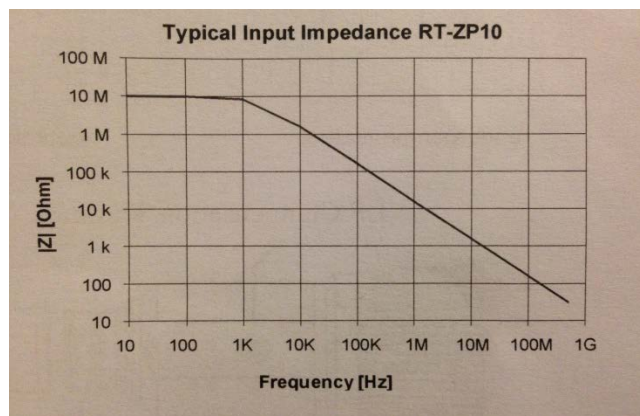


Fig. 3-3: The passive probe input impedance decreases as the frequency increases.

Inside the oscilloscope user manual there should be a similar curve for the passive probes that came with the oscilloscope. At the lower frequency the passive probe starts with an input impedance of around 10 M ohm. However as the bandwidth increases to 500 MHz, the impedance is down around 50 K ohms. Clearly this may have an effect on both the device under test and the signal on the display of the oscilloscope.

### 3.3 Active Probes

A way around the input impedance problem of passive probes at higher bandwidths is to use an active probe. Active probes have a number of benefits in that they are very low loading and have an adjustable DC offset. They are also often recognized by the oscilloscope so that the oscilloscope can automatically set up the correct attenuation factor and other probe settings.

Active probes incorporate Field Effect Transistors or FETs to keep the input impedance higher over a wide frequency range, thus reducing the impact on the device under test, and are typically recommended for signals above 100 MHz or signals with frequency components above 100 MHz.

### 3.4 Probing Best Practices

Next let's discuss probing best practices. First, it is important to use appropriate probe tip adaptor whenever possible. In the past it was not uncommon to add a short length of wire to the probe to make it easier to probe something. At slower speeds that may be acceptable but as applications move up in bandwidth and with higher speed signals this will begin to have a significant impact on the waveform.

Second, it is important to keep ground leads as short as possible. Ground leads will add inductance and will create a ringing on a very fast transition or a fast waveform.

Finally one of the best practices that is often overlooked is to make sure that the probe is compensated to the oscilloscope itself. Sometimes, when in a hurry, one will find an oscilloscope and need to hunt down a few probes, hook them up and start making measurements. Only to later discover measurement errors due to the fact that the probes hadn't been appropriately compensated to the oscilloscope itself.

### 3.5 Selecting Probe Options

There are many probing options that offer different ways to connect to the device under test (Fig. 3-4). This includes things like mini clips and micro clips. There are different adaptors with short ground pins and pogo pins that can be used. Also, there are different headers, such as a square pin header, that make it easier to test that type of connection scheme.

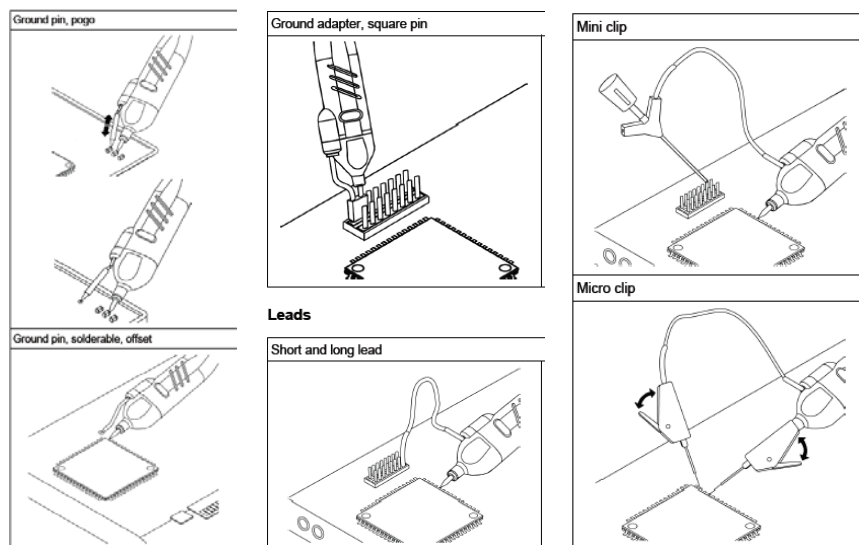


Fig. 3-4: Selecting the right probe options

### 3.6 Improper Compensation

As mentioned before, improper compensation of the probes is something that is typically overlooked. Make sure that the oscilloscope and the probes are properly compensated otherwise the impact on your measurements could be much larger than you might imagine (Fig. 3-5a-c).

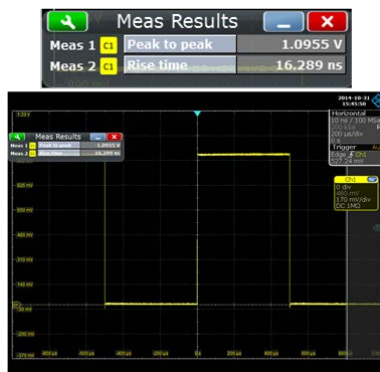


Fig. 3-5a: Properly compensated passive probe shows a nice, square wave. The peak-to-peak is about 1.09 volts and the rise time on that signal is about 16.2, 16.3 nanoseconds

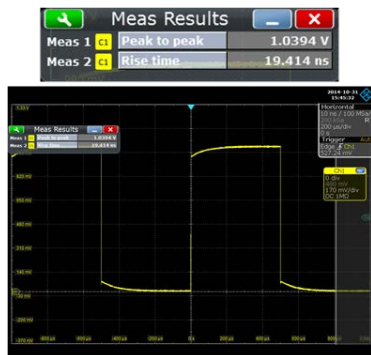


Fig. 3-5b: An improperly compensated probe that is under damped. The peak is now at 1.04 volts and the rise time had a pretty significant impact, about 20 percent - it's up to 19.4 nanoseconds.

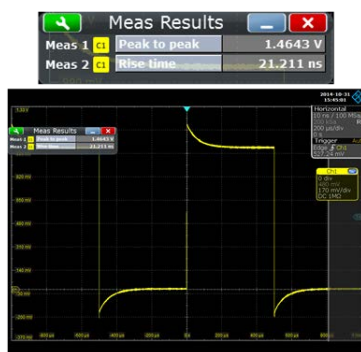


Fig. 3-5c: An improperly compensated probe that is over damped, along with a pretty big overshoot on the signal itself. The peak-to-peak has shot all the way up to 1.46 volts, so a huge discrepancy in what it should actually be reading and the rise time has crept all the way up to 21 nanoseconds.

### 3.7 Ground Leads

Ground leads can have a significant impact on the signal shown on the oscilloscope even on low bandwidth signals. This example uses a 10 MHz square wave, which is a pretty common low speed signal.



Fig. 3-6a: This example used a standard alligator clip or the 15 centimeter long ground lead that comes with the passive probes. This one is a very easy ground lead to use and it's one of the most common ones. The measurement shows a fair amount of ringing on the signal and the overshoot measurement shows about 11.7 percent.

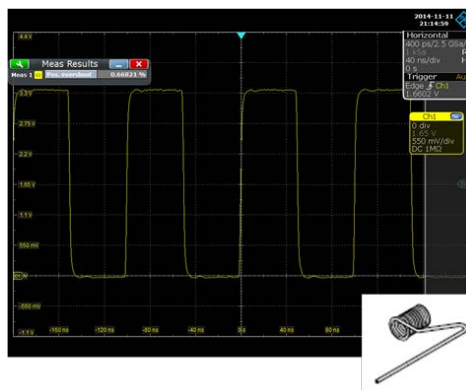


Fig. 3-6b: This example uses a ground spring which gives a nice short ground lead. It gets a much cleaner signal without the ringing that we were seeing on that fast edge before. The measurement overshoot is less than one percent.

### 3.8 Deskew Multiple Channels

Finally, let's focus on using multiple channels of the oscilloscope. Prior to making any measurements the probes have to be appropriately set up and deskewed to compensate for the fact that probes have different electrical lengths. This allows for more accurate measurements across multiple channels and is very important when measuring for example power, with voltage on one channel and current on the other.

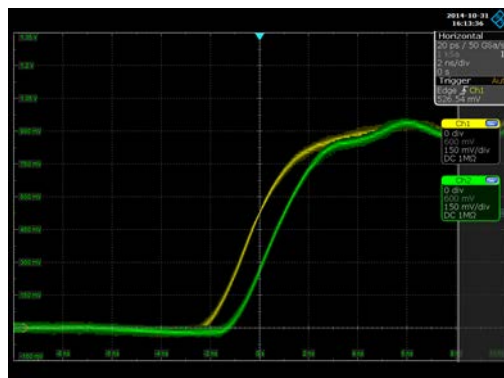


Fig. 3-7a: These two signals, one on channel one and the other on channel two, show a fair amount of skew between them.

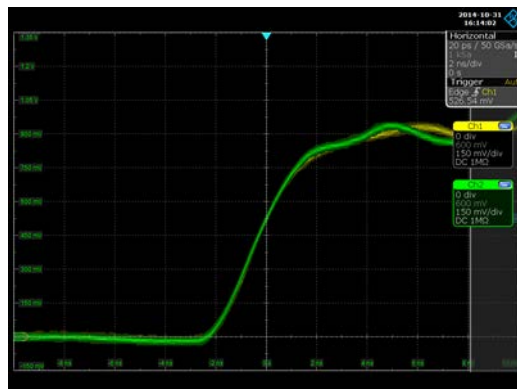


Fig. 3-7b: This is adjusted out by taking the two probes and attaching them to the same probe point. By using the built in deskew capability the skew is removed.

## 4 Vertical System Overview

The controls and parameters of the vertical system are used to scale and position the waveform vertically conditioning the test signal in a way that the analog-to-digital converter (ADC) can then digitize the signal (Fig. 4-1). This is important because ADCs have a very specific range of voltages where they work best. The goal is to attenuate or amplify the incoming signal to optimize the analog to digital conversion process during the digitization of the signal.

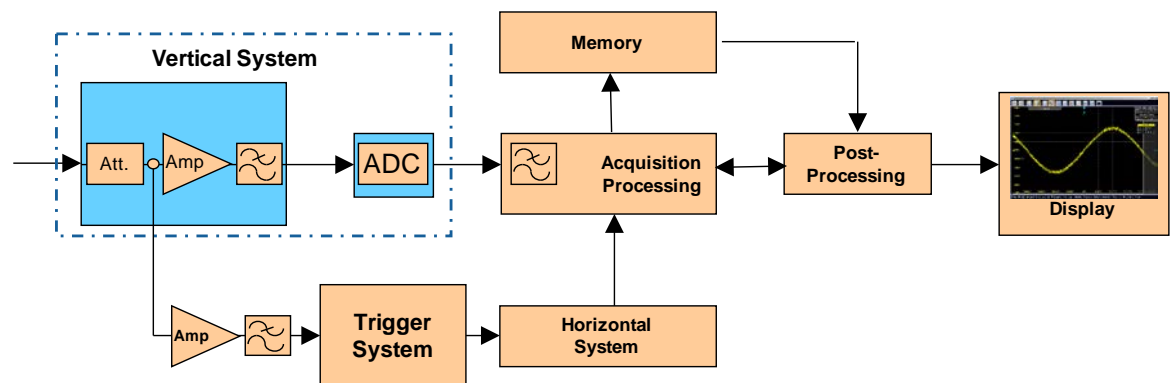


Fig. 4-1: The vertical system function block of a digital oscilloscope

### 4.1 The Vertical System

The vertical system detects the analog voltage and conditions the signal by the attenuator and signal amplifier for the ADC (Fig. 4-2). One of the signal settings is input coupling. There are three different types of input coupling:

- **DC coupling** allows all of the signal to flow through
- **AC coupling** blocks the DC component of the signal and centers the signal around zero volts
- **Ground coupling** disconnects the input signal from the vertical system



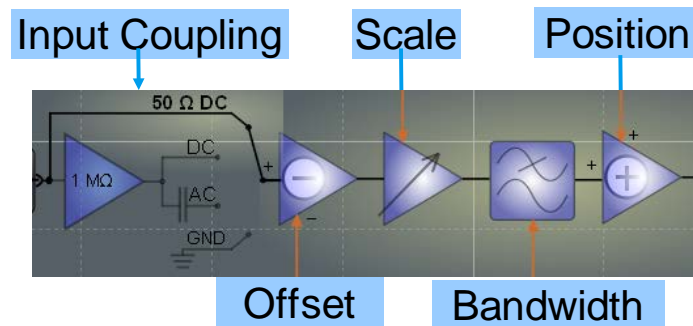


Fig. 4-2: The vertical system detects the analog voltage and conditions the signal by the attenuator and signal amplifier for the analog-to-digital converter (ADC)

AC coupling is useful when the entire signal, the AC and the DC component, is too large for the volt per division setting. This allows the signal to be viewable on the screen of the oscilloscope.

The ground setting disconnects the input signal from the vertical system which allows you to see where zero volts is located on the screen. A useful capability is to combine the ground input coupling and auto trigger mode to show a horizontal line on the screen that represents zero volts. Switching between DC and ground becomes a quick and handy way to measure voltage levels with respect to ground.

General purpose oscilloscopes traditionally have a 1 MΩ input, which is in parallel with a capacitance of around 20 pF. This allows standard oscilloscope probes to attach to the oscilloscope itself and allows for larger voltage ranges into the oscilloscope.

Oscilloscopes at higher frequencies typically have 50 Ω inputs and can either be directly connected to a 50 Ω signal source or used with an active probe.

## 4.2 Analog-to-Digital Converter (ADC)

The ADC in the acquisition system samples the signal at discrete points in time and converts the signal's voltage at these points to digital values called sample points. The ADC is one of the most critical parts of the vertical system. Most manufacturers use custom 8-bit ADCs that are usually not off-the-shelf technology. ADCs are typically measured in both bits of resolution as well as their sample rate or clock rate.

The sample rate is measured in samples per second, such as GS/s, MS/s, all the way down to kS/s or just samples per second. Typically the sample rate should be five times higher than the oscilloscope bandwidth. For example, a 1 GHz oscilloscope will need to have a sample rate of the ADC of 5 GS/s to accurately recreate the wave form.

The ADC collects samples at specific points in time (Fig. 4-3). Each of those sample intervals are equally spaced in time. The sample time interval is going to be specified by one over the sample rate of the oscilloscope. At each sample point there will be a hold time associated with what is required for the digitizing process in the oscilloscope. It then creates a best fit wave form that is the interpolated wave form that is shown in green.

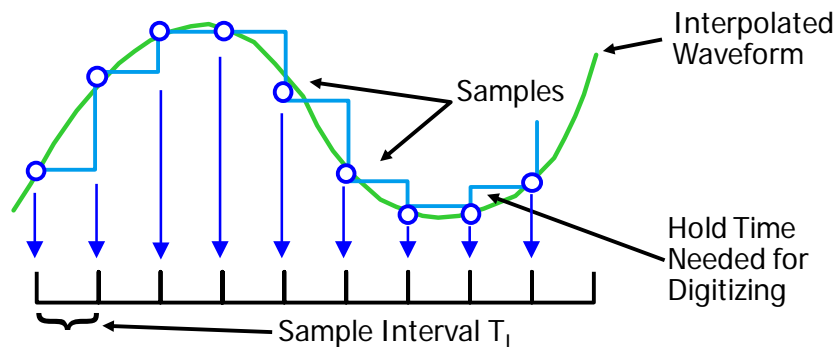


Fig. 4-3: The ADC samples the signal at discrete points in time and converts the signal's voltage to digital values called sample points.

Let's look at an example of how to maximize the ADC input range by taking advantage of the full resolution of the ADC. Fig. 4-4a shows a 500 mV signal amplitude that is scaled to 50 mV per division. This setting is taking advantage of the full resolution of the analog to digital converter because we put it across all of the divisions on the oscilloscope display. At eight bits that's giving about two millivolts per bit. Fig. 4-4b shows a scale of 100 mV per division which does not take as great advantage of the resolution of the ADC with the best resolution being 4 mV per bit. It is important to scale the wave form across as much of the display as possible.

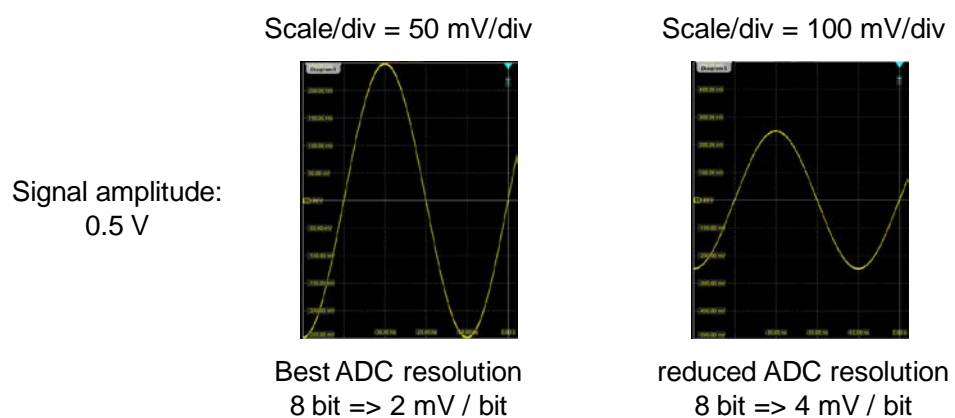


Fig. 4-4a and 4-4b: Maximizing the ADC input range

### 4.3 Improving Vertical Resolution

There are three ways to increase or improve the vertical resolution. One is using averaging, where multiple wave forms are collected and then averaged together to get a higher resolution wave form.

A second one is something that's called high resolution mode or enhanced resolution mode. This method collects additional samples when the oscilloscope is being run at slower sweep speeds. For example, if the digitizer is running at 5 GS/s but the measurement is at a slower sweep speed, all of the sample points may not be used. By averaging on each of those sample points, a higher resolution is achieved (Fig. 4-5).

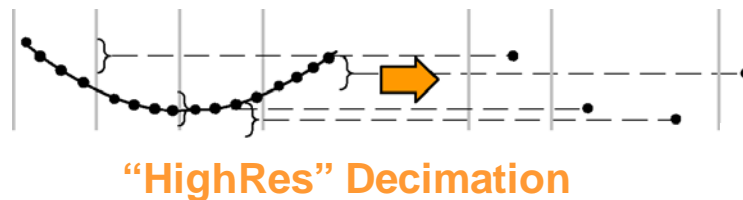


Fig. 4-5: High resolution mode collects additional sample points and averages those into a single sample point for each of those buckets.

The third method uses bandwidth filtering to lower the overall noise of the oscilloscope and thereby increase the signal-to-noise ratio for better resolution. Fig. 4-6 shows the bandwidth filtering block. The signal coming out of the ADC is at 8 bits. Passing through the low pass filter allows a higher resolution, up to 16 bits of resolution in some cases.

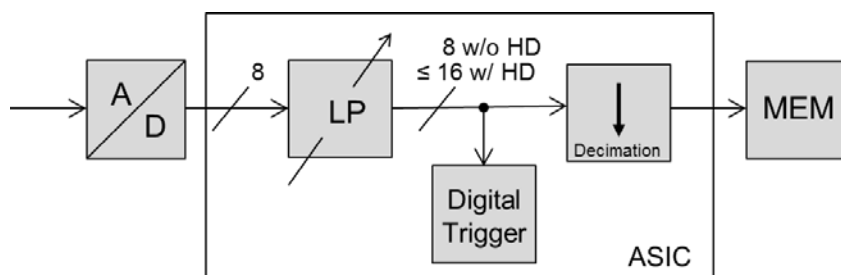


Fig. 4-6: Bandwidth filtering improves resolution by lowering the overall noise of the oscilloscope and thereby increasing the signal-to-noise ratio.

## 4.4 Tradeoffs of Improving Vertical Resolution

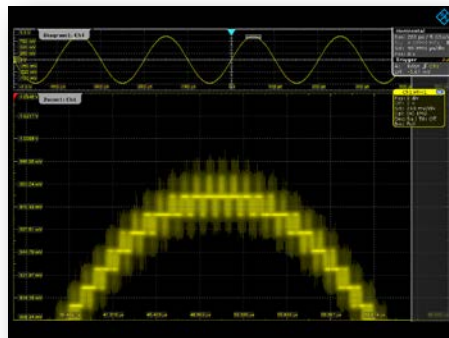
Let's look at a couple examples using these methods to improve vertical resolution. If we are measuring a 10 volt, full screen signal and digitizing that into 256 levels with 8 bits, the smallest signal that can be resolved is 39 mV. However, at 16 bits there are 256 times more levels, or 65,536 levels, that can be digitized. This would now allow the smallest signal that can be resolved to be 152  $\mu$ V. This additional resolution will have a big impact on making more accurate measurements and being able to see small wave forms riding on the top of bigger wave forms.

There are some potential drawbacks when using these methods. For example, using averaging requires a repeatable wave form. If the signal is a pretty dynamic wave form that is changing frequently, averaging is probably not the best way to increase resolution. Averaging a dynamic or changing signal smoothes out the displayed signal, thus masking the characteristics of the actual waveform.

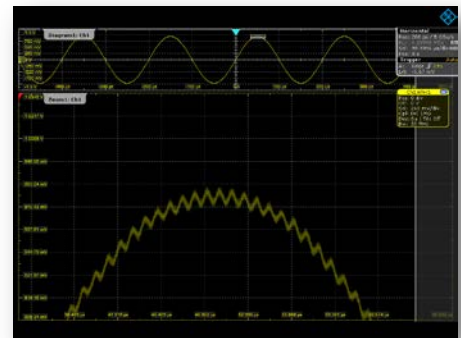
The high resolution method doesn't have this drawback as it can work on a single shot basis. However, it does require a sample rate reduction because it is taking more sample points and averaging them into a single sample point. One of the drawbacks with this mode is that typically the bandwidth is unknown, and as a result it will be difficult to know exactly what the bandwidth of the oscilloscope is at the specific setting. Also, high resolution is usually done post-trigger and this post-processed mode means that the oscilloscope is still triggering on the lower resolution data. If the measurement requires triggering on a very small signal, high resolution is not going to give that ability.

Bandwidth filtering doesn't have the drawbacks of the averaging or the high resolution method. There's no sample rate reduction. And the bandwidth is known because you're actually choosing the bandwidth of the oscilloscope. Most oscilloscopes have a 20 MHz bandwidth filter available and some have additional bandwidth filters as well. One of the big benefits of bandwidth filtering is that the low pass filter is seen by the digital trigger.

[Fig. 4-7a](#) shows a signal that is zoomed in on the very top of a sine wave and in the zoom window there's a fair amount of noise. The quantization steps are also very visible. Turning on the bandwidth filtering and increasing the resolution of the wave form shows the exact same view as before ([Fig. 4-7b](#)). The zoom on the bottom right now highlights that there was some hidden, low-level signal that was riding on top of the main signal. The ability to increase the vertical resolution displayed on the screen of the oscilloscope and lowering the noise improves the signal-to-noise ratio of the oscilloscope itself.



(4-7a) Quantization steps clearly visible



(4-7b) "Hidden" low level signal becomes visible. Signal characteristics can be measured.

Fig. 4-7: Bandwidth filtering does not have the drawbacks of the averaging and high resolution methods.

## 5 Sampling and Acquisition

Now let's review the acquisition processing section of an oscilloscope (Fig. 5-1). One of the key items of any digital oscilloscope is to make sure that there is enough sample rate to not alias the waveform. The Nyquist Rule requires oversampling by at least 2X, the highest signal frequency inside of the waveform to make sure that there is no aliasing.

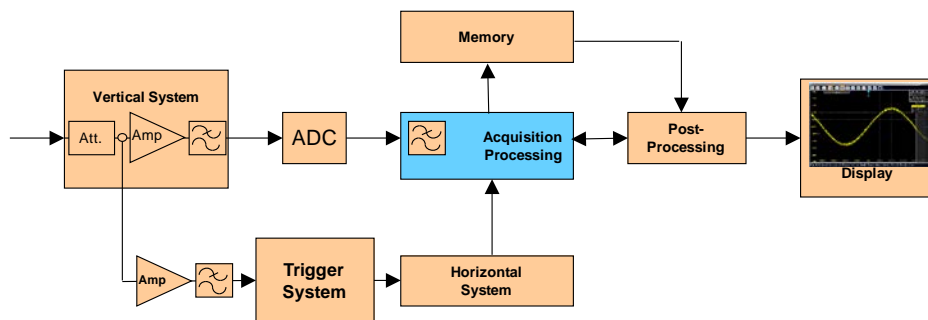


Fig. 5-1: The acquisition processing function block of a digital oscilloscope.

Let's take an example of a 1 GHz sine wave signal. Fig. 5-2 shows this signal as the dotted line. The solid line represents our sampling at 750 Ms/s. This could be because there is not enough memory depth, or the sample rate of the oscilloscope may not be sufficient, or some other reason. When the signal is not sampled fast enough it results in what is known as aliasing of the waveform.

A false reconstructed (alias) waveform is displayed that looks like a signal but it's actually at 250 MHz instead of the 1 GHz signal that was originally put in. By under sampling you end up with a false waveform that is difficult to distinguish from the actual waveform you are inputting and may result in incorrect measurements and incorrect assumptions.

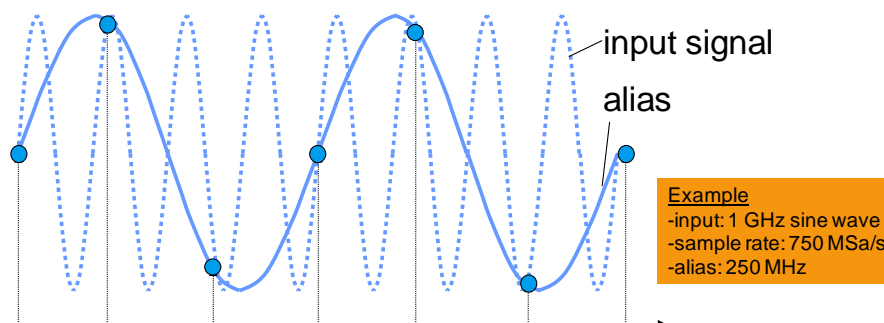


Fig. 5-2: Aliasing occurs when the sampling rate is smaller than 2x highest signal frequency.

## 5.1 Sampling Methods

In an early section we discussed how the ADC in the acquisition system samples the signal at discrete points in time and converts the signal's voltage at these points to digital values called sample points. Now let's talk about sampling methods that interpolate between these points or dots. There are two basic different ways of connecting those dots together.

The first one is linear interpolation. Linear interpolation computes record points between actual acquired samples by using a straight line fit. Fig. 5-3 shows a green line as an example of linear interpolation. As it goes through it just draws a straight line between each of the points, which results in a jagged waveform. Linear interpolation works well on signals that resemble something like a square wave.

The second type of interpolation is called  $\sin(x)/x$  interpolation.  $\sin(x)/x$  interpolation computes record points using a curve fit between the actual values acquired. This will result in a signal that looks much more like a sine wave.

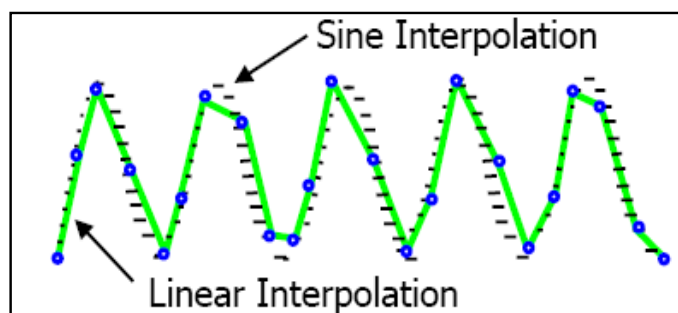


Fig. 5-3: Examples of linear and  $\sin(x)/x$  interpolation.

## 5.2 Acquisition Rates

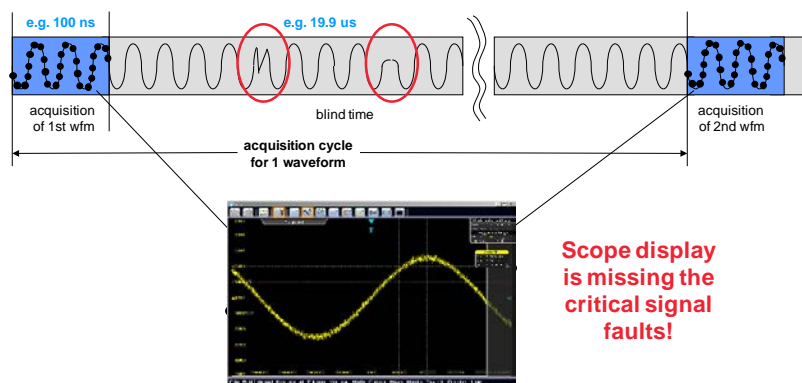
The acquisition rate or waveform update rate is how fast the oscilloscope can trigger, process, and plot information to the display. This specification tells how many waveforms the scope can capture and display, and is typically given in a value of waveforms per second (wfms/s).

In the past, analog oscilloscopes had relatively fast update rates as they were basically taking the beam, deflecting it, and immediately putting waveforms on the screen. The faster this happened, the more likely you were to see infrequent or rare events. People who have used analog scopes might say "Analog scopes really used to show me more information and more signal detail than I see with digital oscilloscopes today."

Waveform update rate, on a digital oscilloscope, is the inverse of dead time. Dead time is the time when the scope is processing and plotting to the display and it doesn't see anything happening in your circuit. The faster the scope can process and plot, the faster the update rate and the greater chance of finding rare events.

Let's take an example of an oscilloscope with an update rate of 50,000 wfms/s (Fig. 5-4). While that sounds really fast, in reality it may not be fast enough. If we were looking at a waveform where we were capturing 100 nanoseconds across a screen, the oscilloscope captures that wave form and then it has to process those waveforms and then plot them to the display (blue). The gray area shows the dead or blind time, when the oscilloscope is unable to see what's actually happening in the device under test. Once the scope is ready again it captures another 100 ns waveform.

From the figure it is clear that we're "awake" or not blind, for 100 nanoseconds and then we're dead for 19.9 microseconds before we wake up to capture another 100 nanoseconds. What's happening during that 19.9 microseconds is unknown and you may be missing rare events. In this example, the oscilloscope is really only active 0.5 percent of the time and 99.5 percent of the time it's blind to what's happening in the device under test. This is why an oscilloscope acquisition rate really matters.



**Fig. 5-4:** Waveform update rates on digital oscilloscope may have significant dead times which could result in missing the critical signal faults

[Table 5-1](#) looks at different waveform update rates and how they relate to how long it might take to capture a rare event. The more frequent the fault, the more likely you are to find it; the less frequent the fault, the longer it's going to take you to find it.



**Table 5-1: Glitch Capture Probability vs. Test Time**

Average measurement time required until a signal error is displayed (as a function of error rate and acquisition rate)

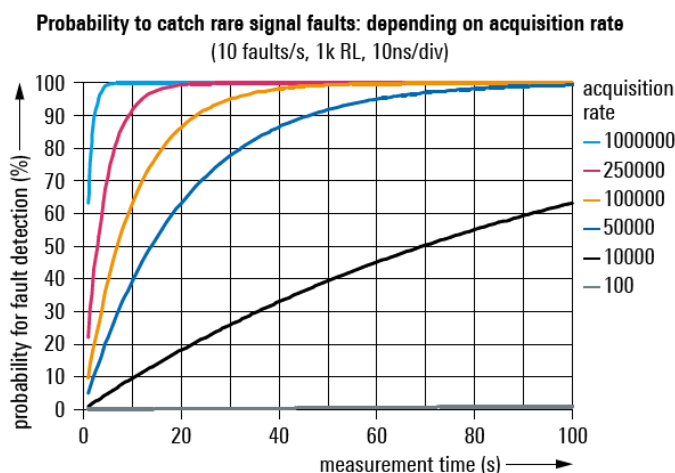
Error rate	Acquisition rate [waveforms/s]			
	100	10 000	100 000	1 000 000
100/s	1 h : 55 min : 08 s	1 min : 09 s	6.9 s	0.7 s
10/s	19 h : 11 min : 17 s	11 min : 31 s	1 min : 09 s	6.9 s
1/s	7 d : 23 h : 52 min : 55 s	1 h : 55 min : 08 s	11 min : 31 s	1 min : 09 s
0.1/s	79 d : 22 h : 49 min : 15 s	19 h : 11 min : 17 s	1 h : 55 min : 08 s	11 min : 31 s

10 Gsample/s, 1 ksample recording length, 10 ns/div, 99.9% probability of detecting the error.

Let's take another example with an error that is happening 100 times per second considering four different acquisition or update rates: 100 wfms/s, 1,000 wfms/s, 100,000 wfms/s and 1,000,000 wfms/s. If we wanted to make sure that we had 99.9 percent probability of detecting that error, with a waveform update rate of 100 wfms/s it would take almost two hours. With the 100,000 wfms/s scope it would only take 7 seconds to see that glitch with 99.9 percent probability. The 1,000,000 wfms/s oscilloscope would take less than one second.

That's a pretty frequent error that happens 100 times per second, what if we consider an error that occurs only once per second? For the 100 wfms/s scope that would take seven, almost eight days to get to 99.9 percent probability. At a 1,000,000 wfms/s it would take a little over one minute.

The trouble with infrequent events is that you may not even know they are occurring. Test time can be decreased tremendously with higher acquisition rates. The best thing you can do it make sure that you have a very fast update rate because that's going to increase your probability of being able to find those infrequent events.

**Fig. 5-5: Probability of catching rare signal faults based on acquisition rates**

## 6 Horizontal Systems

Next let's review the horizontal systems and the relationship between memory depth and sample rate (Fig. 6-1). The horizontal system's sample clock determines how often the ADC takes a sample; the rate at which the clock "ticks" is called the sample rate and is measured in samples per second. The sample points from the ADC are stored in memory as waveform points and these waveform points make up one waveform record.

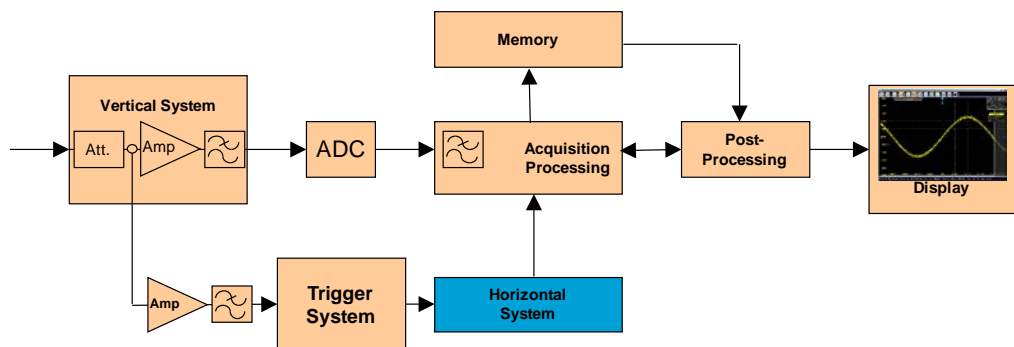


Fig. 6-1: The horizontal system function block of a digital oscilloscope

### 6.1 Sample Rate

Oscilloscopes have a timescale that is measured out in time per division. So if your scope is set at 10 nanoseconds per division and most scopes have 10 divisions across the screen, that's going to give a 100 nanosecond acquisition time. This gives you the amount of time that you're going to capture.

Recall that resolution is basically one over the sampling rate and that is how fast we're going to fill up memory inside the oscilloscope. All digital oscilloscopes have a finite amount of waveform memory (also called record length or acquisition memory), and as the waveforms are digitized the sample points get stored into the memory.

Fig. 6-2 shows an equation that explains how these parameters all come together. Again, sample rate is directly tied back to the bandwidth of the waveform and making sure that we don't alias the waveform. Working through the equation gives the number of points needed / stored at a specific sample rate and time scale.

So what are the advantages of higher sample rates? It offers increased signal fidelity by more accurately reproducing the signal. It gives you better resolution between the sample points, and you can observe high frequency noise in a low frequency signal.

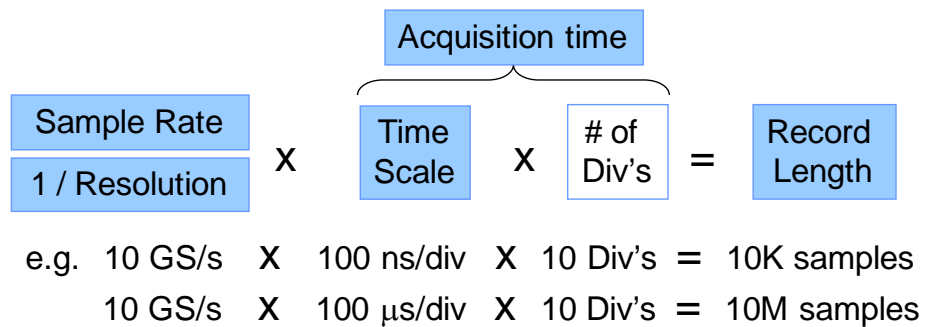


Fig. 6-2: Understanding the relationship between sample rate, acquisition time and record length.

## 6.2 Purpose of Memory

Every sample has to be stored into acquisition memory. Deeper memory allows for the storage of more samples. If you want to capture long periods of time at high sample rates you're going to need to have deep memory. If you don't have very deep memory, then you're going to have to lower the sample rate.

So what are the advantages of deep memory? If you want to capture a long time period while maintaining fast resolution or fast sample rate, that's where having deep memory really comes in to play, because as you zoom in the resolution on a waveform, the time resolution is going to drop and you may not be able to accurately reproduce the waveform.

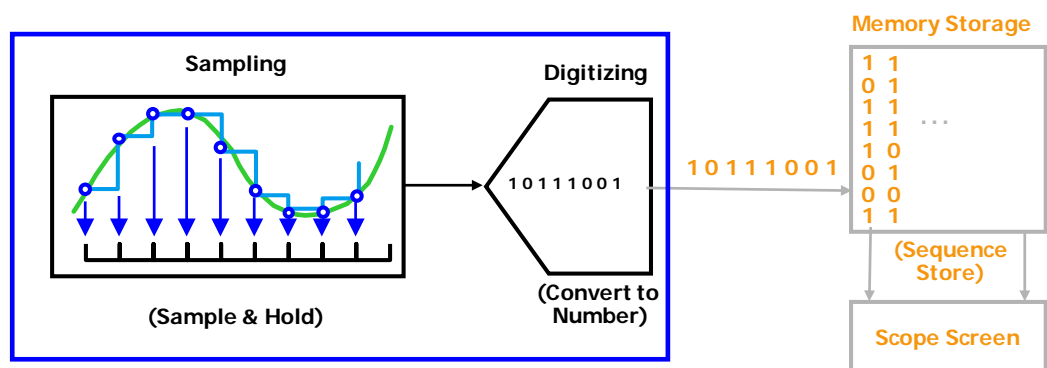


Fig. 6-3: Deeper memory stores more samples into acquisition memory.

## 7 Trigger System

The last section we're going to discuss is the trigger system which is another key function in the overall block diagram of an oscilloscope. When oscilloscopes were first created in the 1930s, one of the challenges was getting a stable display of a repetitive waveform. In 1946 the triggered oscilloscope was invented, allowing engineers to display a repeating waveform in a coherent, stationary manner on the phosphor screen. Triggering allowed for the isolation of events, capturing signals to view them before and after an event. In addition, triggering enabled the definition of a dedicated condition for an acquisition to start.

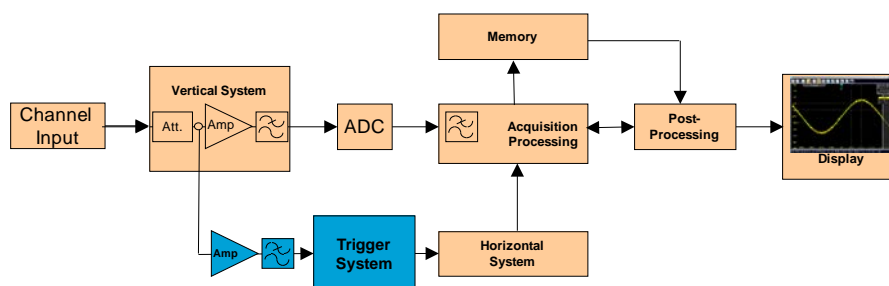


Fig. 7-1: The trigger system function block of a digital oscilloscope.

### 7.1 Trigger Specifications

There are three key triggering parameters to consider when looking at oscilloscopes. The first is - what is the minimum detectable glitch, which is a small signal spike. Basically what's the smallest pulse that the scope can be triggered on and it's typically specified in picoseconds?

Next is sensitivity, which is the minimum voltage amplitude that's required for a valid trigger. If the signal isn't big enough, depending on what the trigger circuitry is expecting, you may not be able to get a stable trigger on the oscilloscope display. This is typically specified in one of two different ways; it's either in millivolts or it's going to be given in a number of divisions or a measure of divisions.

The last specification is around jitter, which is the timing uncertainty of the trigger. It determines the smallest measurable signal jitter and is typically specified in picoseconds rms.

## 7.2 Types of Triggers

Let's look at some of the different trigger types. The Edge Trigger is the original, most basic and most common trigger type (Fig. 7-2). It's the one that most people default to and it's the one that most people use when they're just getting started on capturing a waveform.

An edge trigger is executed once a signal crosses a certain threshold. It could be on a rising edge, a falling edge, or on both a rising and falling edge. But basically you're going to set that trigger level and the oscilloscope is going to trigger when the waveform goes through it.

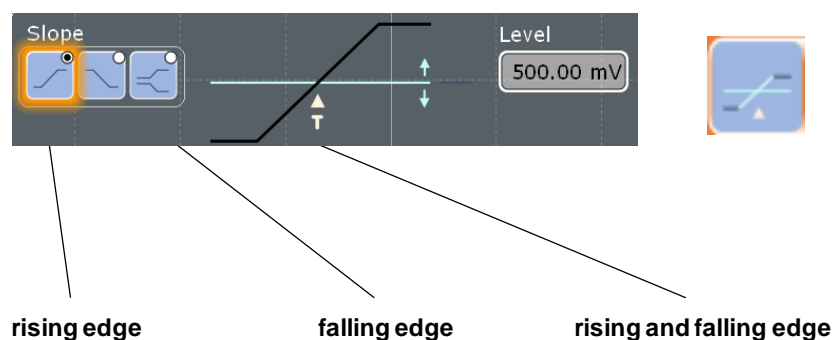



Fig. 7-2: Edge triggering is the most common and basic trigger type.

While edge trigger is probably the most commonly used, oscilloscopes have a number of advanced triggers that allow unique triggering based on the specific type of event that we are trying to isolate. Table 7-1 highlights the different advanced triggers that are commonly available on today's oscilloscopes.

Table 7-1: Advanced Triggering Types

	Trigger Type	Description
	<b>Edge Trigger</b>	Executed once a signal crosses a certain threshold
	<b>Transition time</b>	Slow / fast edges, e.g. circuit instability / radiation of troublesome energy
	<b>Width</b>	Defined pulse width, e.g. observing Inter-Symbol-Interference (ISI)
	<b>State</b>	Logical combination of various channels, e.g. troubleshooting parallel busses
	<b>Glitch</b>	Typically narrow pulse, e.g. caused by cross-talk
	<b>Time out</b>	Dead time, e.g. system errors by wrong dead time relations to other signals
	<b>Window</b>	Event that enters / exits a window , e.g. capture bus contentions
	<b>Setup &amp; Hold</b>	Timing relation between 2 channels, e.g. synchronous data interface
	<b>Runt</b>	Limited amplitude, e.g. meta-stable conditions in digital systems

## 7.3 Mask Violation Triggering

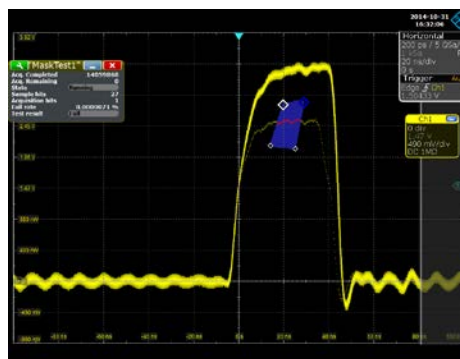
A special triggering type is the mask violation trigger or sometimes also called a zone trigger.

Mask violation triggering allows the user to draw a mask on the display ([Fig. 7-3](#)). This allows you to say if a signal passes through the mask, trigger the oscilloscope on that

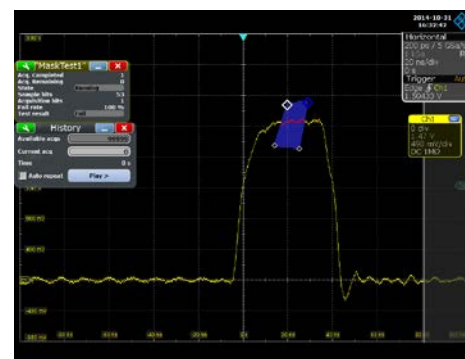
violation. When that happens, the oscilloscope will show the waveform that caused the violation.

A history mode allows you to look back in time, seeing the waveforms that led up to that event. Each waveform is time stamped so that you can see the relative time to the last trigger event or the last waveform that we captured. You can step through the time between those and see the relationship of the signals that led up to the violation that occurred. This makes it simpler to set up a violation than some of the other more advanced triggering techniques.

Finally, mask violations can also be used in the frequency domain as well. So if we were looking at the FFT of a waveform and wanted to trigger if we saw a frequency that we weren't expecting we could draw a box around where that frequency would be. This would give you a time correlated view of the waveform in the frequency domain view too.



(Fig. 7-3a): Draw a mask trigger



(Fig. 7-3b): Capture signals that violate the mask

**Fig. 7-3: Mask violation triggering is often simpler to set up than some of the other more advanced triggering techniques.**






## 8 Summary

This white paper provided a discussion of both oscilloscope and probing basics. You should be able to select the required oscilloscope bandwidth for your application and also determine the proper probe to use. The importance of vertical resolution was reviewed as well as a discussion on getting additional oscilloscope resolution, in addition to an overview on sampling methods and acquisition rates. We also covered horizontal systems, along with the relationship of oscilloscope memory depth and the sample rate. Finally we discussed the trigger system including trigger specifications to pay attention to as well as the different advanced triggers that are available in most modern oscilloscopes.



## 9 R&S Oscilloscope Overview

Applications for oscilloscopes range from debugging complex electronic circuits to measuring the signal integrity of high-speed bus signals and characterizing power electronics with dangerous voltage levels. The following is a brief overview of the oscilloscopes available from Rohde & Schwarz.

Model	Description	Key Facts
<b>R&amp;S®RTO Digital Oscilloscopes</b> 	The R&S®RTO oscilloscopes combine excellent signal fidelity, high acquisition rate and the world's first real time digital trigger system. They also offer hardware-accelerated measurement and analysis functions. Acquisition Rate up to 1 M wfms/s	<ul style="list-style-type: none"> <li>Bandwidth: 600 MHz to 4 GHz</li> <li>Sample Rate: up to 20 GS/s</li> <li>Memory Depth: up to 400 M</li> <li>Vertical resolution: up to 16 bit</li> <li>MSO option: 16 digital channels</li> </ul>
<b>R&amp;S®RTE Digital Oscilloscope</b> 	Truly uncompromised performance from embedded design to general debugging to power electronics analysis the R&S®RTE offers fast and more reliable results. Get signal details at the tip of your finger with FingertipZoom.	<ul style="list-style-type: none"> <li>Bandwidth: 200 MHz to 2 GHz</li> <li>Sample Rate: 5 GS/s</li> <li>Memory Depth: up to 200 M</li> <li>Vertical resolution: up to 16 bit</li> <li>MSO option: 16 digital channels</li> </ul>
<b>R&amp;S®RTM2000 Digital Oscilloscopes</b> 	Turn on and measure. While other oscilloscopes are still booting up, the R&S®RTM is already displaying signals. QuickMeas gives you key measurement results at push of a button.	<ul style="list-style-type: none"> <li>Bandwidth: 200 MHz to 1 GHz</li> <li>Sample Rate: up to 5 GS/s</li> <li>Memory Depth: up to 20 M</li> <li>MSO option: 16 digital channels</li> </ul>
<b>HMO3000 Digital Oscilloscopes</b> 	An excellent sampling rate in combination with a large memory depth is the key for precise signal analysis. The highly resolved measurement data and the powerful zoom function expose even minor signal details.	<ul style="list-style-type: none"> <li>Bandwidth: 300 to 500 MHz</li> <li>Sample Rate: up to 4 GS/s</li> <li>Memory Depth: up to 8 M</li> <li>MSO option: 16 digital channels</li> <li>Optional serial bus analysis</li> </ul>
<b>R&amp;S®HMO1002 Digital Oscilloscope</b> 	High sensitivity, multi functionality and a great price. From embedded developers to service technicians to educators – with its wide range of functions, the R&S®HMO1002 addresses a broad range of applications.	<ul style="list-style-type: none"> <li>Bandwidth: 50 to 100 MHz</li> <li>Sample Rate: up to 1 GS/s</li> <li>Memory Depth: up to 1 M</li> <li>MSO option: 8 digital channels</li> <li>Arb Pattern Generator with 50 MBit/s</li> </ul>

## Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, radiomonitoring and radiolocation. Founded more than 80 years ago, this independent company has an extensive sales and service network and is present in more than 70 countries.

The electronics group is among the world market leaders in its established business fields. The company is headquartered in Munich, Germany. It also has regional headquarters in Singapore and Columbia, Maryland, USA, to manage its operations in these regions.

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## Sustainable product design

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